



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

Ground Based Radio Occultation Measurements Using the GRAS Receiver

Olsen, Laust; Carlström, Anders; Høeg, Per

Published in:

Proceedings of the 17th International Technical Meeting on the Satellite Division of The Institute of Navigation, Long Beach, USA

Publication date:
2004

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Olsen, L., Carlström, A., & Høeg, P. (2004). Ground Based Radio Occultation Measurements Using the GRAS Receiver. In *Proceedings of the 17th International Technical Meeting on the Satellite Division of The Institute of Navigation, Long Beach, USA* (pp. 2370-2377). The Institute of Navigation.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Ground-Based Radio Occultation Measurements Using the GRAS Receiver

Laust Olsen, *Aalborg University*
Anders Carlström, *Saab Ericsson Space AB*
Per Høeg, *Aalborg University*

BIOGRAPHY

Laust Olsen is Ph.D. student at Aalborg University. He received his M.Sc. in Geophysics at University of Copenhagen in 2003.

Anders Carlström is with Saab Ericsson Space AB, where he is working on development projects for space borne GPS receivers and other satellite instruments. He received his Ph.D. in radio and space science from Chalmers University of Technology in 1995.

Per Høeg is professor in Atmosphere and Space Physics at Aalborg University. He received his Ph.D. in Space Physics from the University of Copenhagen in 1987.

ABSTRACT

The dynamics and spectral content of ground based observations of GPS signals are investigated for signs of turbulence. The signals are tracked in open loop mode at 1000 Hz sampling frequency. For mid-latitude winter conditions we see little effect of turbulence inducing spectral broadening. But we are able to identify power spectrum slopes in the frequency range 1-5 Hz that are different from the GPS transmitter clock noise and in direct relation to the elevation angle, indicating weak atmospheric turbulence.

INTRODUCTION

Space-based Radio Occultation (RO) measurements for probing the Earth's atmosphere have been studied extensively during the last decade, see e.g. [1, 2]. In these measurements Global Navigation Satellite System (GNSS) signals are tracked by receivers onboard Low Earth Orbit (LEO) satellites in a geometry where the satellites rise or set behind the Earth's limb as seen from one another. Hence, the atmosphere is scanned from top to bottom, and inversion of the data provides vertical profiles of atmospheric parameters. The RO method provides both global data coverage and a vertical resolution of ~100 meters [3]. This combination is unique for atmospheric sounding techniques, and furthermore, since the method

requires no calibration of the instrument, the data has a great potential for climate studies in addition to weather forecasting [1]. The GNSS Receiver for Atmospheric Sounding (GRAS) will perform RO measurements from the MetOp satellites and this paper presents some initial results from a ground based field test. The objective of this experiment is to establish experimental knowledge on the influence of signal multi-path and other signal disturbances caused by the atmosphere or surroundings as measured by the receiver.

During the past and present RO experiments carried by the satellites MicroSat, Ørsted, CHAMP etc. it has become clear that in the lowest troposphere, GNSS receivers using the Phase Locked Loop (PLL) technique often loses track of the signal [4]. As suggested by Sokolovskiy [5] a more robust way of tracking GNSS signals for RO measurements in the lower troposphere is by use of the Open Loop (OL) technique. In OL measurements the signal tracking are guided by a pre-calculated model of the signal Doppler shift based on the expected satellite positions and velocities and a climatological model of the atmosphere. The model guidance described in [5] can reduce the bandwidth to at most 50 Hz and hence a sampling frequency of 100 Hz is adequate. Similar, but more straight-forward model guidance is used in the GRAS instrument. A ground based field test provides an opportunity to evaluate the capabilities of the 1000 Hz raw sampling function of the GRAS receiver in OL mode.

We present here an analysis of OL data recorded with this receiver at a mid-latitude ground site during January-March 2004. Global Positioning System (GPS) signals are tracked down to negative elevation angles, i.e. below the local horizon. The measurement geometry is sketched in figure 1. The data analysis will focus on signal spectral properties and signal dynamics.

Radio waves propagating in the atmosphere are subject to refraction, diffraction and absorption. In this setup the refraction effect is the most pronounced and causes the slowing and bending of the rays indicated in figure 1. The atmospheric delay alters the Doppler shift of the signal by ~1 Hz compared to the Doppler shift in vacuum [6].

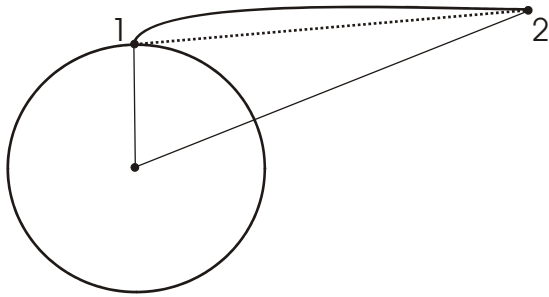


Figure 1: Measurement geometry. The curved line is the signal ray path, while the dotted line indicates the geometrical straight line between the receiver (1) and transmitter (2). Furthermore the radial directions from the Earth's local center of curvature to the receiver and transmitter are displayed by thin solid lines.

The atmosphere causes an overall slowing of the GPS signal, but also broadens the spectral composition of the received signal. This is due to small scale refractivity variations present in the inhomogeneous media. In the atmosphere kinetic energy is dissipated from large scale size disturbances to shorter scale sizes. Atmospheric turbulence is triggered by e.g. convective cells generated by solar heating, but also happens where large wind shear divide horizontal layers of the atmosphere. The latter is the case at the top of the planetary boundary layer (PBL) and near jet streams. Turbulence has the greatest impact on GPS signal propagation in areas where it causes large refractivity gradients, as in the moist tropical troposphere. In this initial study we investigate if we can detect atmospheric turbulence from low elevation GPS measurements.

INSTRUMENT

Overview of MetOp-GRAS

The GNSS Receiver for Atmospheric Sounding (GRAS) is a GPS receiver that operates as an atmospheric-sounding instrument [7, 8]. The GRAS will provide more than 500 vertical profiles per day of the temperature and humidity of the Earth atmosphere using the GPS radio occultation technique. GRAS will fly on MetOp 1, 2 and 3. The first launch is planned for end of 2005. The instrument is designed and produced by Saab Ericsson Space in Sweden. A similar radio occultation instrument has been developed for global scale monitoring of ionosphere electron density and ionospheric scintillation [9].

The GRAS instrument will receive high quality radio signals from GPS navigation satellites, occulting the Earth atmospheric limb, through a tangential path through the Earth's atmosphere. GRAS can track up to eight satellites for navigation purposes, two additional satellites for rising and two others for setting occultation measurements. GRAS performs on-board GPS satellite orbit prediction for optimizing the navigation and occultation measurements.

GRAS is a dual-frequency GPS receiver with semi-codeless-mode operating capabilities. A dual-frequency operating instrument is needed for ionospheric correction. The semi-codeless capability is mandatory in order to mitigate the anti-spoofing (encryption of the precise code), which prevents civilian users from benefiting from the P-code on the L2 frequency. The signals of the occulting satellites (both rising and setting) are received through two antennas, see Figure 2. Shaped antenna patterns (10 dB gain over a ± 45 degree azimuth field of view) and dedicated radio-frequency front-ends ensure a high sensitivity and the ability to measure at low altitudes in the atmosphere – just a few kilometers – where the atmospheric attenuation due to absorption and diffraction is high.

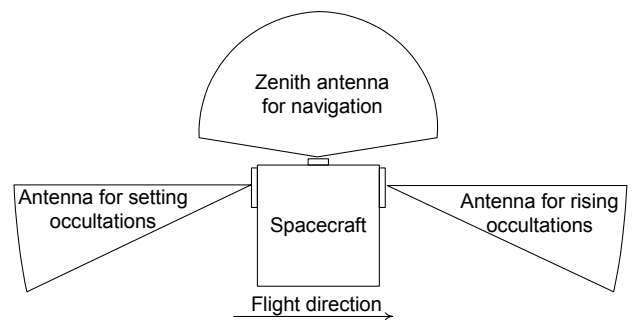


Figure 2: GRAS antenna configuration.

To track the MetOp satellite's position, the instrument also operates as a navigation receiver. In this context, it receives GPS signals via a third antenna with hemispherical coverage, pointing at zenith. It acquires and tracks a set of GPS signals through eight dual-frequency channels and performs a C/A code navigation solution to support the autonomous instrument operation. Within the ground segment, the dual frequency data is used to compute the precise orbit of the spacecraft.

The flight hardware is shown in Figure 3. It consists of one receiver, three front-ends, three antennas, and a deployment mechanism for one of the antennas.

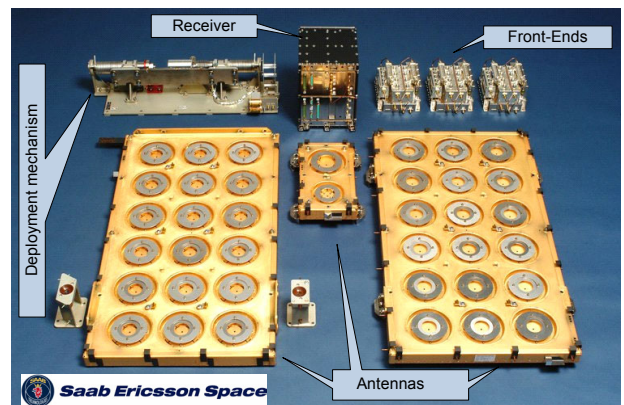


Figure 3: The MetOp-GRAS instrument hardware.

The three antennas point in the satellite's velocity, anti-velocity and zenith directions. The velocity and anti-velocity antennas are phased arrays, each containing 18 patches with a shaped antenna pattern optimized for the occultation of the Earth's limb and its atmosphere. An oven-controlled crystal oscillator is used as a reference oscillator with very stable frequency (Allan deviation of 10^{-12}) in order to retrieve atmospheric measurements with a high accuracy in the stratosphere.

Instrument Set-Up for Ground Based Measurements

The set-up for this experiment consists of in-house prototype electronics (equivalent to MetOp-GRAS), a high gain antenna assembly, and software adapted for ground-based measurements. Figure 4 shows a photograph of the equipment. The antenna assembly - shown in Figure 5 - consists of separate L1 and L2 antennas with a peak gain of >10 dBi to ensure signal detection during severe atmospheric fading events. The main lobe of the antenna is pointed towards the horizon. An ultra-stable rubidium frequency reference is used to control the receiver clock for precise timing of the measurements. The software is modified to select GPS satellites for tracking based on elevation angle and azimuth angle, where the azimuth angle is referred to the geographical North direction. Open loop tracking with raw sampling at 1000 Hz is enforced when the tracked space vehicle (SV) is below a specified elevation angle. Since the receiver is stationary it is also not necessary to perform a navigation solution. The instrument is commanded from a PC, which also is used to store the measurement data.

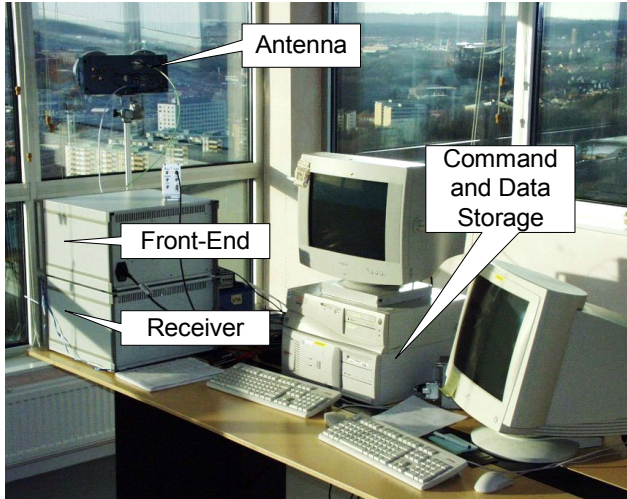


Figure 4: Instrument set-up.

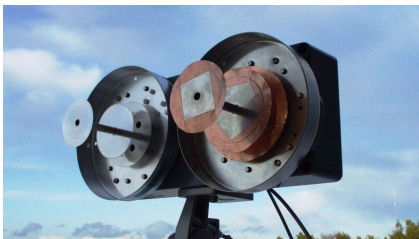


Figure 5: Antenna Assembly (L1 and L2 antennas).

MEASUREMENTS

Initial Measurements in Sweden

An initial data set has been collected during winter conditions in Sweden. The objective was to test the instrument as well as to obtain high latitude data for comparison with tropical data to be collected in the following phase of the experiment.

The measurements were performed from the top floor of the Saab Ericsson Space building in Gothenburg, Sweden, at an altitude of 210 m above sea level. A list of the data collected is shown in Table I. Measurements were made with the antenna pointed in different directions and both with the antenna positioned outdoors and indoors. In the latter case, the measurements were made through the glass of a window.

Table I: Measurement Data Summary

Date & Time (UTC +1h)	Duration	Antenna Azimuth (deg)	Outdoor Antenna	Rising SV	Setting SV
2004-02-26 08:45	2h	240		15	14
2004-02-26 13:55	2h	280		11	8, 27
2004-02-27 11:22	4h	0	x	8, 27, 28	10, 26, 29
2004-03-08 13:33	0.5h	200	x		16
2004-03-08 14:15	1h	300	x		8
2004-03-08 16:41	1.5h	280		4	28
2004-03-09 13:00	3.5h	290		7, 11	8, 27
2004-03-09 17:47	14h	305		10, 14, 17, 18, 21, 22, 24, 25, 26, 29	5, 6, 15, 20, 21, 22, 30
2004-03-10 09:29	2h	205	x	15, 22	25
2004-03-10 12:57	2h	290	x	11	8, 27
2004-03-16 12:30	2h	295	x	11, 28	8, 27

The field-of-view in the North-West direction is shown in Figure 6. The weather conditions during the measurement campaign were typical for the season with temperatures around 0°C and varying degree of cloudiness.

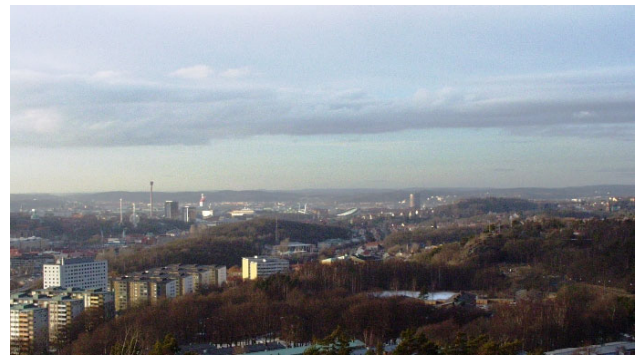


Figure 6: Antenna field-of-view from the top floor of the Saab Ericsson Space building showing the conditions on February 27, 2004.

The GPS satellites are autonomously selected for tracking when they are within a defined window, see Table II. The azimuth limits are selected $\pm 50^{\circ}$ symmetrically around the antenna azimuth pointing direction. The lower elevation limit was always set to -3° . The upper limit was

set to $+30^\circ$ for closed loop tracking and $+5^\circ$ (sometimes $+10^\circ$) for open loop tracking, which is performed in parallel. The closed loop sample rate was set to 10 Hz, except in the last measurement period, where 100 Hz was used.

Table II: Azimuth and Elevation Limits for Tracking

	Tracking window	
	Closed Loop	Open Loop (1000 Hz)
Azimuth	$\pm 50^\circ$	$\pm 50^\circ$
Elevation	-3° to $+30^\circ$	-3° to $+5^\circ$

DATA ANALYSIS

On March 16, 2004, the GPS satellite identified by PRN code number 27 descended in the horizon approximately at local noon. Figure 7 shows the elevation angle of the satellite as function of time, as defined by the instrument clock, while the signal was tracked in OL mode. At time 3159 s the elevation angle is zero degrees and thereafter tracking remains until the elevation reaches -1.23° . The descending rate is roughly 0.3 deg/min.

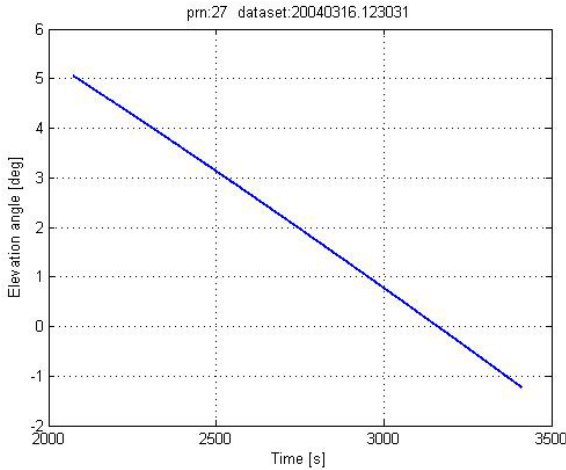


Figure 7: Elevation angle of SV27 during the OL data tracking.

Signal Dynamics

A typical signal amplitude plot is shown in Figure 8 for SV27 when setting below the horizon. The carrier to noise density ratio, C/N_0 , is about 52 dBHz at high elevation angles and then drops during a period of about 200 seconds before the instrument loses track of the code phase at a C/N_0 of about 20 dBHz. The short scale amplitude variations are attributed to fading caused by ground reflection multi-path. At negative elevation angles it is likely that also atmospheric effects are involved in the fading process, although the two effects are difficult to separate.

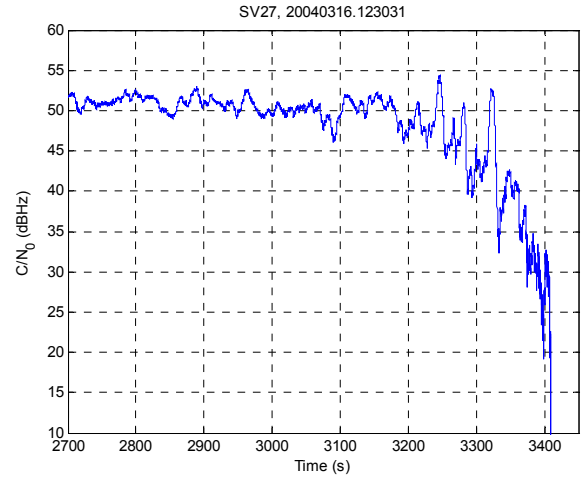


Figure 8: Signal C/N_0 variation for a setting GPS SV.

In figure 9 the carrier signal to noise density ratio for two nearly identical setting occultation events is displayed as function of satellite elevation angle. The two events are chosen to be as similar as possible, but one occurred on March 10, 2004 while the other on March 16, 2004. In both cases SV27 is setting in the same azimuth direction at nearly the same local time, and the antenna was situated the same place and pointed in the same direction. Correlated variations in the two datasets might be attributed to signal interference caused by the surrounding buildings and other solid structures giving rise to reflections, present in figure 6.

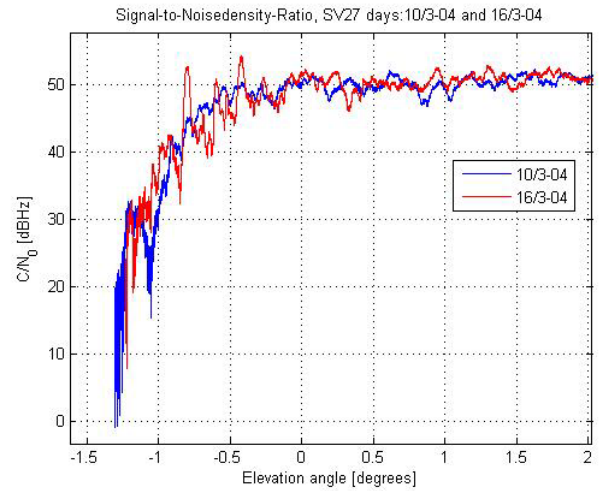


Figure 9: Signal C/N_0 variation for two nearly identical setting events. GPS SV27 on March 10, 2004 (blue line) and on March 16, 2004 (red line).

Spectral content

The main atmospheric modulation of GPS signals in low elevation measurements is attenuation and frequency shift due to ray bending, whereas the presence of turbulence is expected to cause a spectral broadening of the signal. In figure 10 the power spectrum estimate based on a discrete Fourier transform of approximately 131 s of 1000 Hz sampled OL data is given. The elevation angle of the GPS

satellite at the center of the data window is 4.77 degree, and the window length corresponds approximately to 0.6° elevation angle change.

Displaying the power spectrum as function of frequency difference, $f - f_0$, from the main signal peak, f_0 , on a logarithmic frequency scale reveals the characteristic domains of the spectrum. Up to 10 Hz the spectrum is approximately sloping as f^{-2} , while in the frequency range [10:500] Hz the spectrum is flat. The latter part of the spectrum originates from thermal noise while the f^{-2} sloping part is characteristic for the rubidium frequency references used in both the GPS transmitter and the receiver. Clock correction (differencing) has not been applied to the data.

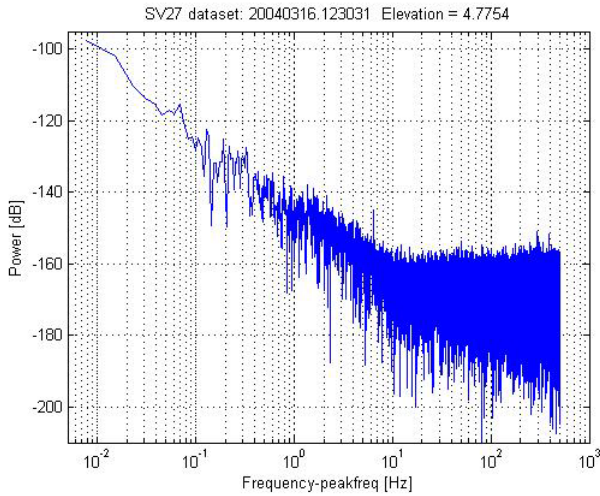


Figure 10: Power spectrum estimate of 1000 Hz OL data of SV27 on March 16, 2004, at 4.77° elevation.

When producing a spectrum at lower, and negative, elevation angles, a more irregular spectrum is observed, see figure 11.

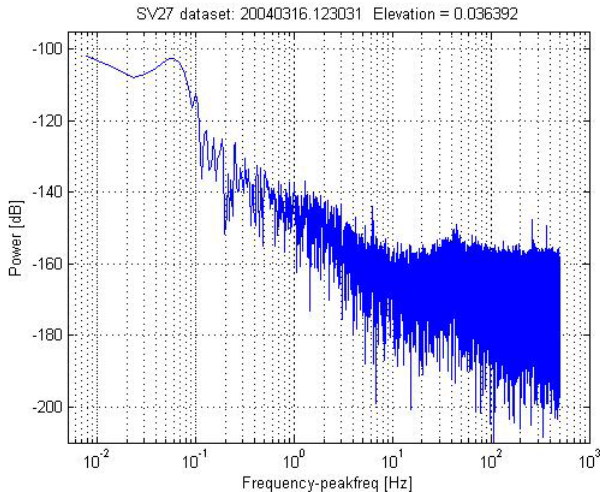


Figure 11: Power spectrum estimate of 1000 Hz OL data of SV27 on March 16, 2004, at 0.04° elevation.

This is mainly due to the change of Doppler shift, caused by smooth background atmosphere, over the time of the

data window. In figure 12 we see that the 131 s data window corresponds to a change in Doppler shift of the order 0.2 Hz.

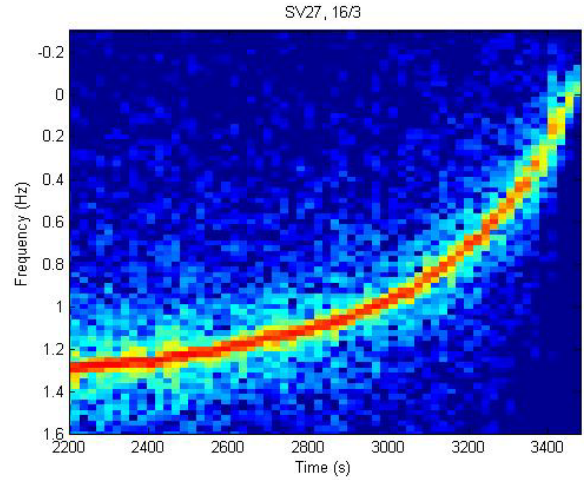


Figure 12: Zoom in on the main signal peak in the sliding power spectra.

The background signal frequency drift can be removed by subtracting a least squares fit parabola to the phase when constructing the spectrum. In this case we obtain the plot shown in Figure 13 which does not show any indication of periodic variations with periods of 40 seconds or less. The turbulence of the atmosphere at this location is thus not large enough to cause detectable spectral broadening of the signal.

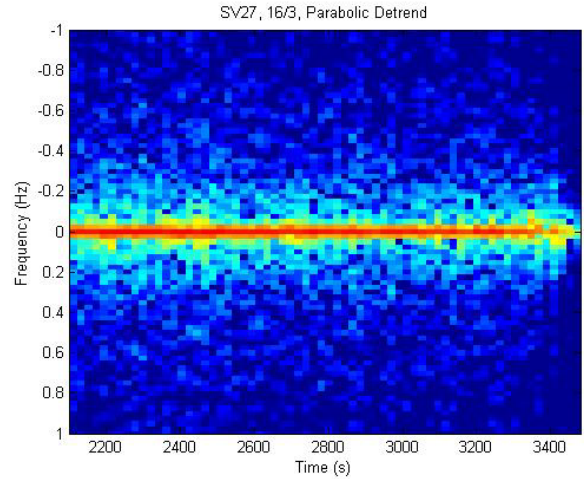


Figure 13: Sliding discrete spectrum of phase de-trended data. The frequency resolution is 1/40 Hz.

We analyzed the trend of the mean slope in the spectra for the frequency domain 1 - 5 Hz, which should be above the frequencies affected by multi-path and continuous signal Doppler shift and below the transition to the thermal noise dominated part of the spectrum. Only in some cases we were able to detect a slightly increased slope as function of the elevation of the received signal above the horizon. Figure 14 shows the slope variation, which could be an indication of weak turbulence and eddies in the beam direction, since lower elevation angles indicate increased

spectral mean slope. This follows the general picture of atmospheric turbulence, where scale lengths have longer horizontal scales than vertical. We have not included the negative elevation angle data in the least squares fit in figure 14, since we believe, that the slope trend there are caused by the rapidly decreasing SNR.

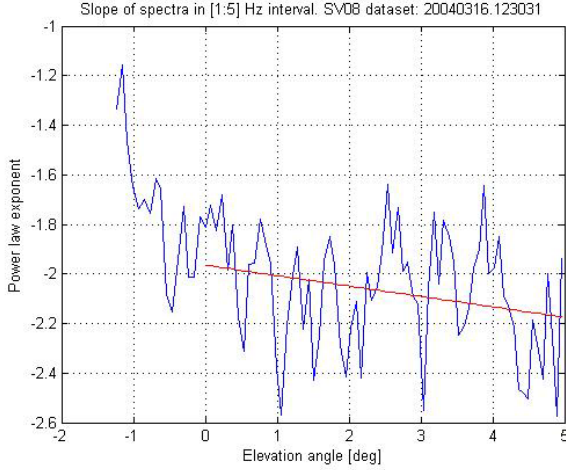


Figure 14: Example of the variation of the slope of the [1:5] Hz interval of the power spectrum estimate, as function of elevation angle. The straight red line is the linear least squares fit to the curve in the $[0^\circ:5^\circ]$ interval.

The major part of the measurements gave similar results to the example presented in figure 14. In most of these data sets the mean spectral trend was including other noise terms not having the same spectral characteristics.

Co-channel Interference

The 1000 Hz data collected in the open loop mode shows clearly the effect of co-channel interference between satellites. The interference is due to the short length (1023 chips) of the C/A code, which results in a level of cross correlation between the codes of -30 dB on average and -22 dB in the worst case. Figure 15 shows sliding spectra versus time for the setting occultation of SV27 on 16/3.

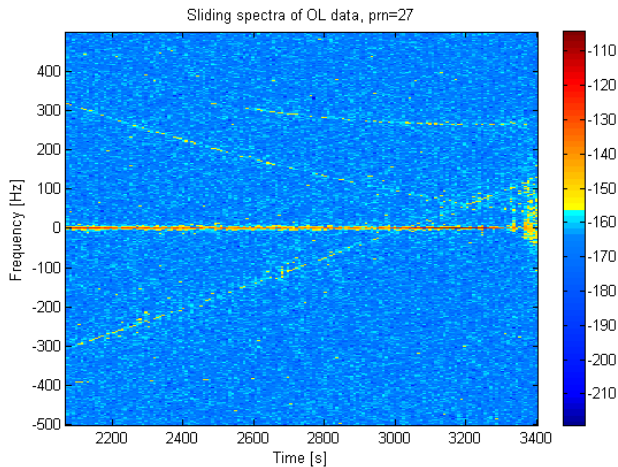


Figure 15: Traces of co-channel interference at the -30 dB level from SVs 8, 11, and 28 in the power spectrum plot for SV27.

The interfering signals from SVs 8, 11, and 28, can be seen as line traces at the -30 dB level in the plot with a frequency offset varying with the relative Doppler shift of the SVs. The frequency offset of the traces corresponds exactly with the expected Doppler shift calculated from almanac data, see figure 16, which confirms that the spectral lines are caused by co-channel interference.

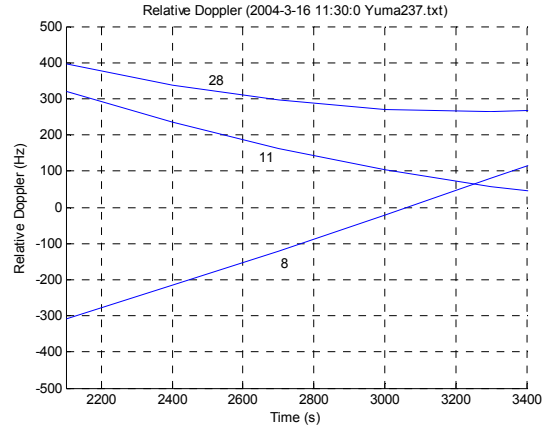


Figure 16: Expected Doppler frequency (modulo 1000 Hz) for SVs 8, 11, and 28 relative to SV27.

DISCUSSION

We have analyzed the signal dynamics and spectral content of low elevation GPS measurements in OL tracking mode. We find that the high-frequency part of the signal is dominated by thermal noise, while the lower frequency part are dominated by clock-noise, which for the receiver rubidium clock falls off as the inverse of the frequency squared. It has not been possible generally to separate a contribution to the signal power caused by small scale atmospheric structures, overlaying the clock noise in the spectra. This is in accordance with that the data presented in this study were representative for winter extra-tropical conditions. Under these atmospheric conditions the atmospheric turbulence is not as severe for GPS signals, due to the minor content of water vapor, as opposed to tropical conditions. In the tropical atmosphere much more vapor is present and hence we expect the spectral broadening might become significant.

In order to study atmospheric turbulence by spectral analysis of low elevation data, the turbulence have to impose stronger spectral fluctuations above the noise characteristics of the clock.

In the signal amplitude plots we see non-periodic fading patterns with rapid variations of up to 20 dB, which could be caused by atmospheric multi-path combined with ground surface reflections. The fact that the pattern did

not repeat for two measurements made on different days with the same geometry indicates that atmospheric effects are present, though. The analysis methods developed for this data set are expected to be capable to reveal atmospheric multi-path and potential turbulence under tropical conditions. Mountain top measurements in tropical atmosphere are planned to be performed in the next phase of the experiment during October 2004.

The open loop data collected at 1000 Hz shows evidence of co-channel interference from other SVs at the -30 dB level. This is in agreement with theory and shows that the open loop tracking of the GRAS instrument performs as expected.

ACKNOWLEDGMENTS

This work is supported by the Swedish National Space Board and the Danish Technical Research Council. We also acknowledge the Swedish National Testing and Research Institute for providing the rubidium clock.

REFERENCES

- [1] E. R. Kursinski, G. A. Hajj, J. T. Schofield, R. P. Linfield and K. R. Hardy, "Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System", JGR 102 D19, pp. 23429-23465, 1997.
- [2] R. Ware, et al., "GPS Sounding of the Atmosphere from Low Earth Orbit: Preliminary Results", Bull. Am. Meteorol. Soc., 77, pp. 19-40, 1996.
- [3] M. D. Mortensen, R. P. Linfield and E. R. Kursinski, "Vertical resolution approaching 100 m for GPS occultations of the Earth's Atmosphere", Radio Science 34(6), 1475-1484, 1999
- [4] S. V. Sokolovskiy, "Modeling and inverting radio occultation signals in the moist troposphere", Radio Science, 36(3), 441-458, 2001
- [5] S. V. Sokolovskiy, "Tracking tropospheric radio occultation signals from low Earth orbit", Radio Science 36(3), pp. 483-498, 2001.
- [6] S. V. Sokolovskiy, C. Rocken and A. R. Lowry, "Use of GPS for estimation of bending angles of radio waves at low elevations" Radio Science, 36(3), 473-482, 2001.
- [7] P. Silvestrin, R. Bagge, M. Bonnedal, A. Carlström, J. Christensen, M. Hägg, T. Lindgren, F. Zangerl, "Spaceborne GNSS Radio Occultation Instrumentation for Operational Applications", in Proceedings of ION GPS 2000, September 19-22, 2000, Salt Lake City, Utah, pp. 872-880.
- [8] M. Loislet, N. Stricker, Y. Menard, J.-P. Luntama, "GRAS – Metop's GPS-Based Atmospheric Sounder", ESA Bulletin, No.102, May 2000.
- [9] A. Carlström, R. Emardson, J. Christensen, P. Sinander, F. Zangerl, G.B. Larsen, P. Hoeg, "The GPS Occultation Sensor for NPOESS", in Proceedings of IGARSS 2002, June 24-28, 2002, Toronto, Ontario, Canada.